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Sealing Ability of Three Fiber Dowel Systems

Virgínia Santos, DMD, MS,[1,2] Jorge Perdigão, DMD, MS, PhD,[3] George Gomes, DMD,[4] & Ana Luísa Silva, DMD[2,5]

[1]Assistant Professor, Department of Removable Prosthodontics, University of Lisbon School of Dentistry, Lisbon, Portugal
[2]Former graduate student, MS Program in Operative Dentistry, Instituto Superior de Ciências da Saúde Egas Moniz (ISCSEM), Caparica, Portugal
[3]Professor, Division of Operative Dentistry, Department of Restorative Sciences, University of Minnesota, Minneapolis, MN
[4]Clinical Instructor, Postgraduate Program in Operative Dentistry, ISCSEM, Caparica, Portugal
[5]Clinical Assistant Professor, Department of Operative Dentistry, University of Lisbon School of Dentistry, Lisbon, Portugal

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Correspondence
Jorge Perdigão, University of Minnesota School of Dentistry, 515 SE Delaware St, 8-450 Moos Tower, Minneapolis, MN 55455. E-mail: perdi001@umn.edu

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Abstract

Purpose: To study the sealing ability of two new fiber dowel systems.
Materials and Methods: Thirty-six extracted single-rooted teeth were endodontically treated and randomly assigned to two new fiber dowel systems and a control group: (1) an E-glass-based dowel, everStick-POST, cemented with ParaCem Universal DC resin cement (EV); (2) a glass-fiber dowel, RelyX Fiber Post, cemented with RelyX Unicem self-adhesive resin cement (RX). The control group was restored with a glass-fiber dowel, ParaPost Fiber Lux, cemented with ParaCem Universal DC resin cement (PP). The roots were isolated and immersed in a 50 wt% ammoniacal silver nitrate solution for 24 hours followed by 8 hours in a photo-developing solution. The roots were sectioned in 1-mm-thick disks perpendicular to the long axis of the root. The specimens were processed for backscattered FESEM observation. For each tooth, the depth of silver infiltration into the root canal was measured by ranks from 0 to 8. For each disk, silver infiltration was measured as the percentage of leakage around the adhesive interface. Data were analyzed with Kruskal-Wallis nonparametric tests at a significance level of 95%.
Results: When the silver infiltration was computed from the coronal to the apical aspects of the root, RX resulted in the lowest degree of silver infiltration, but not statistically different from that of EV ($p < 0.148$). RX, however, resulted in a lower depth of silver infiltration than the control group PP at $p < 0.023$. EV resulted in a statistically similar depth of penetration to PP ($p = 0.492$). Although the total mean percentage of silver infiltration at the dentin-resin cement interface was statistically similar for all groups ($p = 0.632$), EV resulted in the greater number of disks with silver infiltration (23 out of 96), followed by PP (21 out of 96) and RX (14 out of 96). None of the specimens showed leakage around the dowel-resin cement interface.
Conclusion: The use of the E-glass dowels in EV did not improve the root-wall sealing ability compared with the control group PP. The system RX, which uses a new simplified self-adhesive protocol, resulted in a lower depth of silver infiltration than the control group PP.

The restoration of root-canal-treated (RCT) teeth is still a challenge for the clinician. RCT teeth are often restored with a dowel-and-core to replace tooth structure lost by caries, restorative procedures, fractures, or endodontic access preparations.[1] The use of dowels when the crown is clinically damaged is a universally accepted clinical procedure to gain retention for the core and resist lateral forces.[2]

The use of fiber-reinforced resin (FRR) dowels to restore RCT teeth has gained popularity in the last few years. This popularity is a consequence of several factors: (1) The enhanced esthetic properties of FRR dowels; (2) FRR dowels can be cemented with an adhesive technique;[3,4] (3) Although cast dowels are mechanically stronger,[5] the modulus of elasticity of FRR dowels is similar to that of dentin, resulting in lower incidence of root fractures.[6] Forces in the tooth restored with an FRR dowel are apparently absorbed by the core and dowel, preventing the fracture of the tooth structure, reducing the stress accumulation in the root walls as compared to other dowel types;[6,7] (4) The bond strengths of FRR dowels to root canal dentin are higher than those of ceramic dowels.[8]

Current FRR dowels are white opaque or translucent, which benefits the final aspect of the restoration.[9] They are composed of unidirectional quartz or glass/silica fibers embedded in a resin matrix.[10] Fibers are pretensioned, and then the resin is injected under pressure to fill the gaps between fibers, giving them a solid cohesion. The microstructure of each dowel is based on the diameter of each fiber, on its density, and on the adhesion quality between fibers and matrix. The addition of fibers to a polymeric matrix results in an improvement of mechanical properties such as fracture resistance, stiffness, and fatigue resistance.[10]

More recently, a new bendable and moldable dowel material has been introduced. This dowel is based on E-glass continuous and unidirectional fibers embedded in a polymer network known as the IPN, or the interpenetrating polymer network. The commercial name for this new material is everStick-POST (StickTech Ltd., Turku, Finland).[11] The matrix contains linear phase polymers, polymethacrylathe (PMMA), and a cross-linked polymer 2,2-bis[(4-2-hydroxy-3-methacryloloxypropoxy) phenylpropane] (poly bis-GMA).[12] The PMMA-rich phase is located at the surface of the dowel material. It has been claimed that the luting cement is able to interpenetrate the polymer linear phase and polymerize within the structure of the everStick dowel.[12] This interpenetrating ability may be able to increase the bond strengths between these new dowels and resin cements.[11] As a result of this more intimate bonding, the resin cement-dowel interface may be less prone to adhesive failures with the IPN-based dowels as compared to the other dowel systems. In spite of several recent studies focused on dowels based on IPN technology, there is a lack of information regarding the adaptation of everStick dowels to the root canals.

To test the sealing at the coronal dentin/restoration interface, a combination of infiltration tests with electron microscopy has been suggested.[13] This method, in addition to showing the quality of the hybrid layer, allowed the observation of a dye at the dentin/restoration interface, even in the absence of gaps.[14] This type of infiltration was named as nanoleakage.[15] The difference between microleakage and nanoleakage resides in the dimension of the spaces that allow silver infiltration (20 to 100 nm) compared to spaces in the range of 10 to 20 μm that occur with microleakage.[15,16] Silver infiltration was first thought to be a result of the permeation of silver into the nanometric spaces around collagen fibers that had not been completely enveloped by the adhesive monomers or when these monomers were not able to displace residual water.[15] More recently, other studies suggested that the presence of nanometric spaces within the hybrid layer might result from the incomplete polymerization of the adhesive and from the presence of low molecular weight oligomers.[17-19]

While silver infiltration is used to assess the quality of dentin-resin hybrid layers at a nanometric level, a pilot study in our laboratory showed that the same methodology can be applied to a root canal model to test the ability of dowel systems to prevent the penetration of silver ions into the interface formed by the root canal walls and the dowel-resin cement system. The success of endodontic therapy is frequently reported in terms of apical sealing with coronal sealing having an important role as well.[20] Ideally, dowels cemented in the root canal must provide a tight seal along the walls and along the cement-dowel interface.[9]

Loss of adhesion at the fiber dowel-dentin interface is still the main reason why these restorations fail.[21] Currently, there is a lack of information on the sealing ability of dowel systems (dowel and luting cement) in the root canal. Therefore, the objective of this study was to test the sealing ability of three dowel systems. The null hypothesis tested is that the use of two new systems of dowels with their respective cements (an IPN-based fiber dowel luted with conventional resin cement, and a quartz-fiber dowel luted with simplified self-adhesive cement) does not improve the sealing of root dentin walls when compared to a widely tested quartz-fiber dowel system used as control.

Materials and methods

Thirty-six extracted, single-rooted teeth were selected and stored in a 0.2% chloramine at 4°C for less than 2 months. To standardize the sample, the teeth had similar morphology, size, and root shape, without previous root canal treatment. The teeth were cleaned with periodontal curettes to remove the residual soft tissues and analyzed under a stereomicroscope (Motic Digital Stereo-microscope, Richmond, Canada) to check for the integrity of the root surfaces. The teeth were randomly assigned to three dowel systems (n = 12). Each dowel system consisted of a fiber dowel and a resin cement. The materials and respective manufacturers are listed in Table 1.

Root canal treatment

The crowns were ground 4 mm above the most apical region of the cementoenamel junction (CEJ) using a high-speed diamond bur under water irrigation (SUPERtorque LUX 660B, Kavo Dental GmbH, Biberach, Germany). The canal access was prepared with a #6 carbide round bur (SS White Burs, Inc., Lakewood, NJ) at high speed under abundant water. The working length was determined by subtracting 1 mm from the length at which a no. 10 K-file tip (FFDM Pneumat, Bourges, France) extruded from the apex.

The enlargement of the coronal and medium thirds of the root was achieved using Gates-Glidden drills (FFDM Pneumat) #4, #3, and #2 in a crown-down succession. Each drill was used in four teeth and then replaced. Apical preparation was performed using stainless steel 0.02 taper #15 and #20 K-files (FFDM Pneumat) to the working length. The irrigation and lubrication regimen was carried out using 5.25% NaOCl (The Clorox Company, Oakland, CA). Root canals were irrigated with 1 ml of 5.25% NaOCl between instruments using a syringe with a side-vented 23-gauge needle (Discardit II, BD, S.A., Madrid, Spain). The canal was kept full of irrigant during the cleaning and shaping phases. The final irrigation was performed with 1 ml of 5.25% NaOCl, followed by 2 ml distilled water.

Following the final irrigation, the canal spaces were completely dried with absorbent paper points (Meta Dental Co., Elmhurst, NY). The prepared canals were coated with root canal sealer (AH26, Dentsply DeTrey, Konstanz, Germany), using a

Table 1 Materials used

Material (batch numbers)	Type	Composition [12,36]	Manufacturer
everStick-POST* (Dowels: 000039, 000043, 000076; Resin: 5604336)	Moldable IPN dowel	Unidirectional E-glass, PMMA, Bis-GMA	StickTech Ltd., Turku, Finland
ParaPost Fiber Lux (MT-52625)	Fiber-glass dowel with parallel shoulders	Unidirectional translucence fiber-glass (60%) and epoxy resin fiber (40%)	Coltène/Whaledent, Altstätten, Switzerland
RelyX Fiber Post (045080612)	Tapered fiber-glass dowel	Unidirectional translucent fiber-glass	3M ESPE, St. Paul, MN
ParaCem Universal DC (ParaCem Base: 0094400; PareCem catalyst: 0100872; ParaBond nonrinse conditioner: lot 0103108; ParaBond adhesive A: lot 0100885 ParaBond adhesive B: lot 0100886)	Self-etch 2-step adhesive and dual-cure resin cement	ParaBond self-etch adhesive –*Nonrinse Conditioner*: water, acrylamidosulfonic acid, hydroxyethyl methacrylate –*Adhesive A*: hydroxyethyl methacrylate, glycerol monomethacrylate, glycerol dimethacrylate, polyalkenoate methacrylate maleic acid, benzoyl peroxide –*Adhesive B*: ethanol, water, initiators ParaCem resin cement –*Catalyst:* Bisphenol A diglycidyl methacrylate, bisphenol A diethoxy methacrylate, triethylene glycol dimethacrylate, barium glass silanized, amorphous silica, benzoyl peroxide –*Base*: Bisphenol A diglycidyl methacrylate, bisphenol A diethoxy methacrylate, triethylene glycol dimethacrylate, barium glass silanized, amorphous silica, initiators	Coltène/Whaledent, Altstätten, Switzerland
RelyX Unicem (250291)	Dual-cure self-adhesive cement	–Powder: glass fillers, silica, calcium hydroxide, self-cure initiators, pigments –Liquid: methacrylated phosphoric esters, dimethacrylates, acetate stabilizers, self-cure initiators, light-cure initiators	3M ESPE, St. Paul, MN

*Stick-Resin—BisGMA, TEGDMA.

PMMA = polymethylmethacrylate; Bis-GMA = 2,2-bis[(4-2-hydroxy-3-methacryloloxypropoxy) phenylpropane].

Combinations of materials used in this study are EV = everStick-POST + ParaCem Universal DC; RX = RelyX Fiber Post + RelyX Unicem; PP = ParaPost Fiber Lux + ParaCem universal DC.

Sources used are as follows:

3M ESPE Glass Fiber Post, RelyX Fiber Post Technical Product Profile, 2006.

ParaCem Universal DC—Instructions for use, Coltène/Whaledent, 2006.

ParaPost Fiber Lux—The Ideal Post System for Laboratory and Office, Coltène/Whaledent, 2005.

ParaPost Fiber Lux Esthetic Post System, Instructions for use, 2004 (http://www.coltenewhaledent.biz/download.php?file_id=3838&PHPSESSID=3da967f8947f7a5464346f14eaaf4b86).

ParaCem Universal, Instructions for Use, 2007 (http://www.coltenewhaledent.biz/download.php?file_id=3414).

StickTech—Instructions for Root Canal Restoration, 2003 (http://www.sticktech.com/instructions2003/view.asp?id=IND06&lang=ENG).

tapered gutta-percha master cone and secondary cones (Meta Dental Co.) with the latero-vertical condensation technique.

After endodontic treatment was complete, the access was sealed with a resin-modified glass-ionomer cement (Vitrebond, 3M ESPE, St. Paul, MN),[22] which was light-cured for 40 seconds using a 2500 Curing Light (3M ESPE). The specimens were then stored for 7 days in 100% humidity in individually numbered dark opaque vials.

Dowel insertion

Dowel holes were prepared to a depth of 12 mm from the occlusal reference, leaving an apical seal of 4 to 5 mm of gutta-percha in the canal space after dowel preparation. Gutta-percha was removed with a warm plugger to the appropriate depth. All root canals were prepared with #3 Gates-Glidden drills followed by the calibration drills of each dowel system (Table 2). Each set of drills was used in four teeth and then discarded.

Group 1—everStick-POST + ParaCem Universal DC (EV). The dowel diameter and length were selected after the canal was rinsed with saline and dried with paper points. Dowels of smaller diameter were added to the main dowel to fill the extra canal space when the canal aperture was elliptical. One coat of bonding resin (Stick-Resin, StickTech Ltd.) was brushed on the surface of each accessory dowel before they were attached to the master dowel. The adaptation of the dowels to the root canal walls was checked by inserting and removing the dowel three times, followed by light curing for 40 seconds (2500 Curing

Table 2 Characteristics of dowel/drill systems used in this study

Dowel	Gutta-percha removal	Root canal preparation		
everStick-Post	Gates-Glidden no. 3	No drill supplied by the manufacturer; thickness of prepolymerized dowel material: 0.9 mm, 1.2 mm, 1.5 mm		
ParaPost Fiber Lux	Gates-Glidden no. 3	Drill/Dowel color code (dowel number)	Drill/Dowel diameter	
		Red (#5)	1.25 mm	
		Purple (#5.5)	1.40 mm	
RelyX Fiber Post	Gates-Glidden no. 3	Dowel color code	Drill/Dowel coronal diameter	Drill/Dowel apical diameter
		Yellow	1.30 mm	0.70 mm
		Red	1.60 mm	0.80 mm

Light, 3M ESPE) from the occlusal aspect while the dowel was inserted in the canal. The surface of the shaped final dowel was then coated with Stick-Resin, and the dowels stored for 3 to 5 minutes in a dark environment while the canal was being prepared, as per manufacturer's instructions. The surface of the dowels was slightly air-dried to thin out the adhesive resin, and then light cured for 10 seconds. After the application of the respective two-step self-etch adhesive, ParaCem Universal DC Base and ParaCem catalyst (Coltène/Whaledent, Altstätten, Switzerland) were mixed and applied on the surface of each dowel, and the dowels were inserted carefully in the root canal. After removing excess cement, the dowel system was left undisturbed for 4 minutes to allow for the chemical polymerization of the cement.

Group 2—RelyX Fiber Post + RelyX Unicem (RX). The root canal was rinsed with distilled water and dried with paper points (3M ESPE). The dowel surface was wiped with ethanol before and after the dowel was tried in, followed by drying with oil-free air. The root canals were then cleansed with 2% NaOCl for 1 minute, rinsed with water, and dried with paper points. RelyX Unicem Universal shade A2 (3M ESPE) was dispensed through an elongation tip, and the dowel was inserted as per the manufacturer's instructions. After removing excess cement, the dowel was left undisturbed for 5 minutes.

Group 3—ParaPost Fiber Lux + ParaCem Universal DC (PP, control). The root canals were calibrated starting with the #3 ParaPost drill (Coltène/Whaledent). The drill diameter was increased sequentially to reach the size of the dowel that matched the canal diameter. After the dowel adaptation to the root canal was checked, the canals were rinsed with distilled water for 1 minute and dried with paper points. The dowel surface was then wiped with ethanol gauze. After the application of the respective adhesive, ParaCem Universal DC Base and ParaCem catalyst (Coltène/Whaledent) were mixed, and the dowels were cemented as per the manufacturer's instructions. After removing excess cement, the dowel was left undisturbed for 4 minutes.

A diagram of the methodology is shown in Figure 1. All specimens were stored in dark opaque vials with distilled water

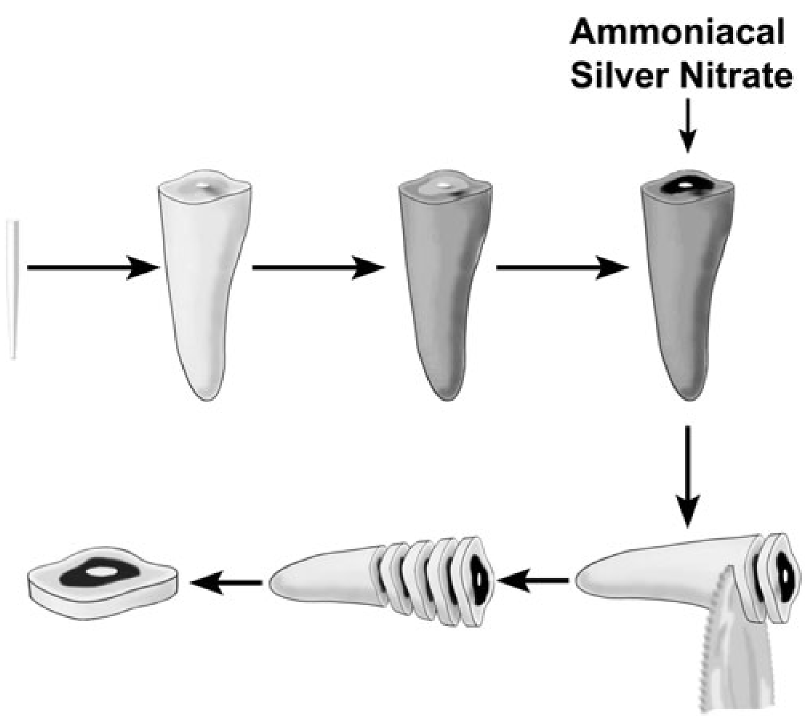

Figure 1 Diagram of methodology used.

at 37°C for 24 hours. The bonded specimens were then fixed to phenolic ring forms (Buehler Ltd., Lake Bluff, IL) filled with acrylic resin (Trayresin, Dentsply/Trubyte, York, PA). The dowels were kept parallel to the acrylic table and fixed with sticky wax. The ring forms with the mounted specimens were attached to an Isomet 1000 Precision Saw (Buehler Ltd.) keeping the root perpendicular to the saw blade. The teeth were then sectioned 0.5 mm above the CEJ to remove residual resin cement and the coronal part of the dowels.

Silver infiltration test

The specimens were coated with two layers of nail polish, except for a 1.0 mm rim around the root canal, to allow the contact of the tracing agent with the adhesive interface. Then, the specimens were immersed in an aqueous solution of 50 wt% ammoniacal silver nitrate[23] (pH = 10.0) for 24 hours at 37°C. The specimens were removed from the tracing solution, rinsed with running water for 1 minute, and immersed in a photo-developing solution for 8 hours to permit the reduction of silver ions to metallic silver grains.[23] This basic silver nitrate solution was used to prevent the possibility of artifactual dissolution of remnant calcium phosphate along resin-tooth interfaces with the use of an acidic silver nitrate dye. The specimens were rinsed again in running water for 1 minute, and the nail polish was removed.

Preparation for FESEM

The specimens were fixed in 2.5% glutaraldehyde in a 0.1 M sodium cacodylate buffer at pH 7.4 for 12 hours at 4°C.[26] After fixation, the specimens were rinsed with 20 ml of 0.2 M sodium cacodylate buffer at pH 7.4 (Ted Pella, Redding, CA) for 1 hour with three changes, followed by distilled water for 1 minute. The specimens were dehydrated in ascending grades of ethanol as follows: 25% for 20 minutes, 50% for 20 minutes, 75% for 20 minutes, 95% for 30 minutes, and 100% for 30 minutes. The roots were then sectioned in a mesiodistal direction with a diamond saw (Isomet 1000, Buehler Ltd.) to obtain 1.0-mm-thick disks, starting with the most coronal disk (Fig 1). Each disk was marked on the coronal side with an indelible marker for identification purposes. The occlusal surface of each disk was polished with waterproof silicon carbide papers of decreasing abrasiveness (800- and 1200-grit), followed by soft tissue disks with increasingly fine suspensions of 1 μm and 0.3 μm (Buehler Ltd.) for 1 minute each. The disks were ultra-sonicated in 100% ethanol for 10 minutes, thoroughly dried, and demineralized in 0.5% silica-free phosphoric acid for 1 minute to remove polishing debris. All slices were scanned at a high resolution (per group) in an Epson Perfection 4990 Photo Scanner (Epson America, Inc., Long Beach, CA) and observed under a Motic Digital Stereo-microscope (Motic North America). Then, the specimens were evaporated with carbon for 1 minute (DV 502A Vacuum Evaporator, Denton Vacuum, Moorestown, NJ) and observed under a Field-Emission Scanning Electron Microscope (FESEM) with a Autrata-modified YAG detector (S-4700, Hitachi High Technologies America, Inc., Pleasanton, CA) at an accelerating voltage of 8.0 kV and working distance of 13.5 to 14.0 mm. The magnifications were automatically corrected for working distance.

Table 3 Ranking of silver infiltration according to the depth of infiltration into the root canal

Ranks	Description
0	No silver penetration detected
1	Silver observed in disk 1, but not reaching disk 2
2	Silver observed in disk 2, but not reaching disk 3
3	Silver observed in disk 3, but not reaching disk 4
4	Silver observed in disk 4, but not reaching disk 5
5	Silver observed in disk 5, but not reaching disk 6
6	Silver observed in disk 6, but not reaching disk 7
7	Silver observed in disk 7, but not reaching disk 8
8	Silver infiltrated down to the most apical disk (disk 8)

Silver infiltration was assessed using two methods: (1) the depth of penetration into the root canal was analyzed by dividing each tooth into ranks from 0 to 8 (Table 3). (2) Silver deposition was measured in each disk by delimiting the reticular metal deposition in the backscattered FESEM micrographs using image software (ImageJ 1.38r, National Institutes of Health, Bethesda, MD). The percentage of silver penetration was measured around the bonded interface for each disk using the formula $N = (C/P) \times 100$, where N is the percentage of silver infiltration at the bonded interface, C is the length of silver penetration (μm), and P is the total length of the interface.[15]

Statistical analyses

As the significance of the normality test was not strong (Blom method, $p = 0.07$), the percentage of silver infiltration around the adhesive interface was analyzed nonparametrically. Therefore, Kruskal-Wallis nonparametric tests were used to analyze the two data sets at $p < 0.05$; the data corresponding to ranks of infiltration depth into the root canal and the percentage of silver infiltration around the adhesive interface for each disk. The software SPSS 14.0 for Windows (SPSS Inc., Chicago, IL) was used for all tests.

Results

When the silver infiltration was computed from the coronal to the apical depth of the root canal (Table 4), RX resulted in the lowest degree of silver infiltration, but not statistically different from that of EV ($p = 0.148$). RX, however, resulted in a lower degree of leakage than the control group PP at $p < 0.023$. EV resulted in a statistically similar depth of penetration to PP at $p = 0.492$. The analysis of percentage of silver deposition around the dentin-resin cement interface for each disk showed no statistical difference ($p = 0.632$) for any pair of dowel systems (EV = 8.2 ± 1.8%; PP = 8.9 ± 2.3%; RX = 6.3 ± 1.9%).

Silver deposition was observed in the most coronal disk (disk #1) for all teeth. The maximum depth of silver infiltration by tooth is shown in Table 4. Out of a total of 96 disks analyzed for each group, 23 disks in the EV group displayed silver infiltration; in the PP group, 21 disks were infiltrated; 14 disks showed the presence of silver infiltration in the RX group (Table 5).

Table 4 Maximum depth of silver infiltration by tooth (ranks, 0–8*)

	Tooth 1	Tooth 2	Tooth 3	Tooth 4	Tooth 5	Tooth 6	Tooth 7	Tooth 8	Tooth 9	Tooth 10	Tooth 11	Tooth 12
EV[ab]	2	1	1	1	6	4	2	1	1	2	1	1
RX[a]	1	2	1	1	1	1	2	1	1	1	1	1
PP[b]	1	1	3	1	3	2	3	1	2	2	1	1

*Groups with the same superscript letter resulted in statistically similar silver penetration into the root canal at $p < 0.05$.

The FESEM observations are displayed in Figures 2 to 4. No evidence of silver deposition was present at the dowel-resin cement interface, only at the dentin-resin cement interface. Some disks displayed residual gutta-percha. This residual gutta-percha was consistently associated with silver deposition at the interface with dentin (Figs 2A and 4A). For groups EV (Fig 2) and PP (Fig 3), porosities were observed at the dentin-resin cement interface in more than 50% of the specimens. In most cases, the interfacial porosity displayed silver penetration (Fig 2B). For RX, on the other hand, very small pores were only observed in the resin cement, without silver infiltration (Figs 4B and D). Figures 2E and 3A and B show areas of separation between the resin cement and the dentin substrate associated with silver infiltration.

While for PP and RX the dowel-resin cement interface followed a circular line corresponding to the circular cross-section of the dowels, for EV the same interface had an irregular contour (Figs 2B and C). This irregular contour was especially visible in the canals in which extra EV fibers had been coated with Stick-Resin to make the dowel fit to the elliptical shape of the canal. The dowel-cement interface in group RX displayed areas in which the cement filler particles infiltrated the dowel surface layer (Fig 4E).

The evaluation of all dentin disks highlighted the close resemblance in the distribution of individual fibers between PP and RX. For EV, the individual fibers were not organized consistently, with areas in which the fibers were missing (Fig 2D). The cross-sectional arrangement of fibers for groups PP and RX was very similar.

Discussion

Ammoniacal silver infiltration has been used to evaluate the sealing ability and the quality of the hybrid layer[14,24] to test the deterioration of the bondings[25-27] by hydrolysis of resin and collagen fibers in coronal dentin.[26] In the present study, a similar methodology was used to test the sealing ability of fiber dowel systems to root canal dentin.

Apart from the difficult access and the lack of direct vision within the root canal, the interaction between the high C-factor inside the canal (ratio of bonded to unbonded surfaces)[28] and polymerization shrinkage of resin materials results in stresses that may jeopardize the adhesive cementation of intraradicular dowels.[29] The resin material has an opportunity to flow when more free surfaces are available, which results in relaxation of stresses that develop in the polymerizing resin.[28,30] Internal shrinkage stresses in the cement inside the root canal may separate the cement from the dentin wall.[31] These shrinkage stresses were responsible for the resin cement-dentin interface debonded areas observed by other authors.[21,31]

Although interfacial gaps were observed between the resin cement and dentin, they did not occur between the resin cement and the fiber dowel. This selective debonding has been described by other authors.[31,32] Discontinuous gaps between resin cement and dentin were observed; however, there was a good adaptation between cement and the dowels used.[32]

In the present study, high variances were most likely a result of the following contributing factors: (1) 80% of the disks (230 out of 288, Table 5) were assigned a rank of "zero" in the statistical analyses; (2) the complexity of the root canal anatomy and differences in dentinal tubule number and orientation in the root canal system.

ParaCem dual-cure resin cement was hand mixed. Large voids were observed at the dentin-cement interface on specimens cemented with ParaCem, which was used in both the EV and PP groups. This may have been due to air bubbles entrapped within the cement.[3,31] The use of a lentulo spiral might have reduced the prevalence of voids.[3] The incorporation of air in the resin has been shown to inhibit the polymerization of the cement.[33,34] The deleterious effect of a high C-factor may actually be compensated for by the stress relaxation provided by the air in the structure of the resin material.[34] Consequently, it may be speculated that the use of hand-mixed resin cements to lute fiber dowels may be of some benefit for the mechanical integrity of the resin-dentin interface as it provides an opportunity for the stresses accumulated in the resin cement to dissipate, at

Table 5 Dentin disks with silver penetration by the dowel system (n = 12)

	Most coronal disk⟷Most apical disk								
	Disk 1	Disk 2	Disk 3	Disk 4	Disk 5	Disk 6	Disk 7	Disk 8	Total
EV	12/12	5/12	2/12	2/12	1/12	1/12	0/12	0/12	23/96
RX	12/12	2/12	0/12	0/12	0/12	0/12	0/12	0/12	14/96
PP	12/12	6/12	3/12	0/12	0/12	0/12	0/12	0/12	21/96

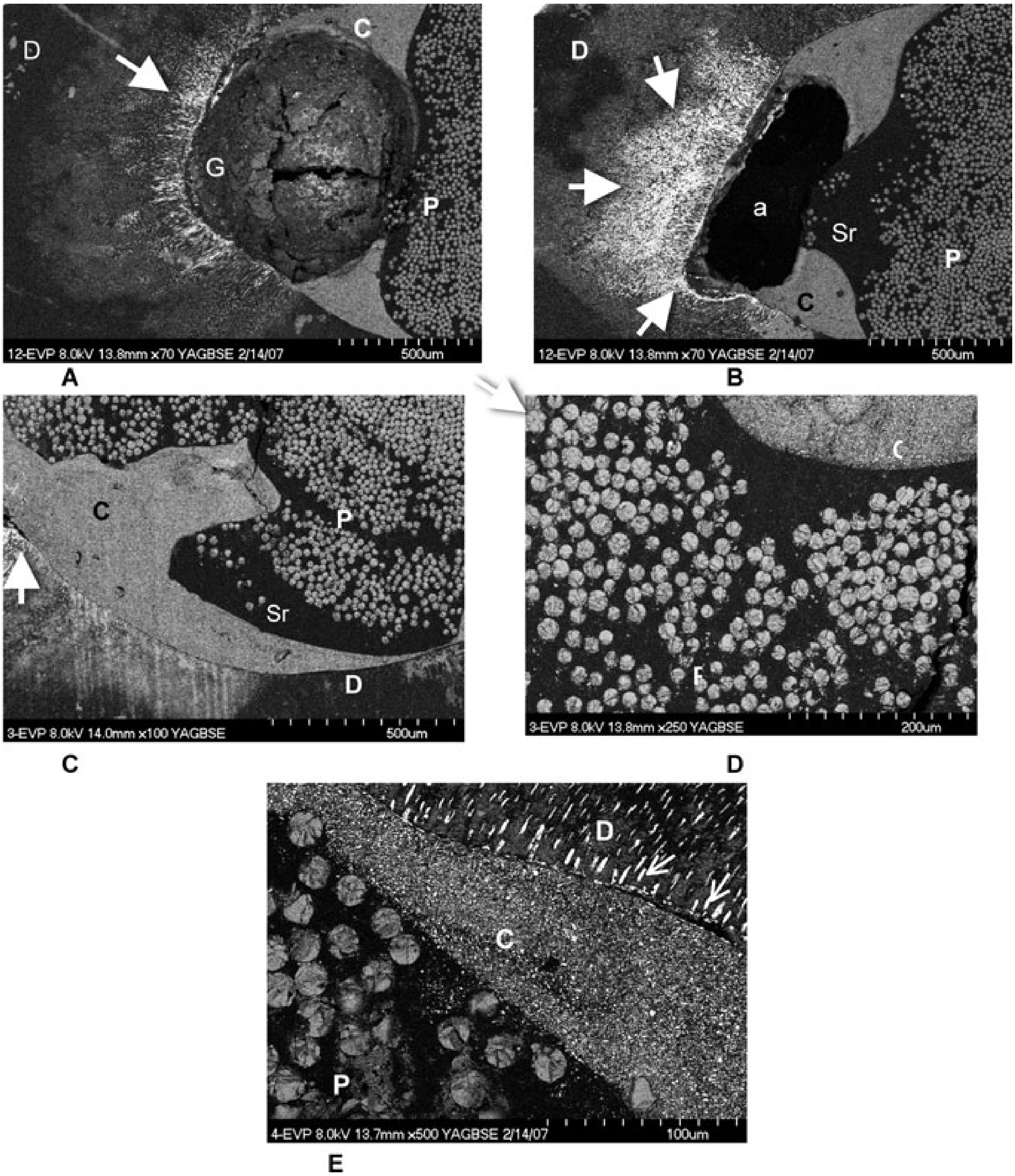

Figure 2 FESEM analyses of EV system: (A) residual gutta-percha with silver infiltration (arrows) (backscattered FESEM image, slice 2); (B) empty area (a) within the cement layer displaying silver infiltration (arrows) (backscattered FESEM image, slice 1); (C) irregular contour of the dowel as compared to groups PP and RX shown in Figs 3A and 4B, respectively (backscattered FESEM image, slice 1); (D) individual fibers in the EV system were not as condensed as in the other two groups (backscattered FESEM image, slice 2); (E) silver infiltration into the dentinal tubules (backscattered FESEM image, slice 1); P = Dowel; C = Cement; D = Dentin; G = Residual gutta-percha. Sr = Stick-Resin. The μm units shown in the micrographs correspond to the entire scale of 10 divisions.

least partially.[34] Notwithstanding this benefit, air bubbles may weaken the composite, which may explain in part the debonding between the resin cement and the root dentin and the greater silver infiltration scores at this interface. One might also speculate that, besides the type of mixture, the large voids found at the dentin-ParaCem interface were caused by the higher viscosity of this cement compared to that of RelyX Unicem, since viscous cements have less ability to flow into the space between dentin and the dowel. In fact, our observations confirmed that the presence of voids at the dentin-cement interface was associated with greater silver infiltration. In contrast, small voids were only found in the body of RelyX Unicem and were

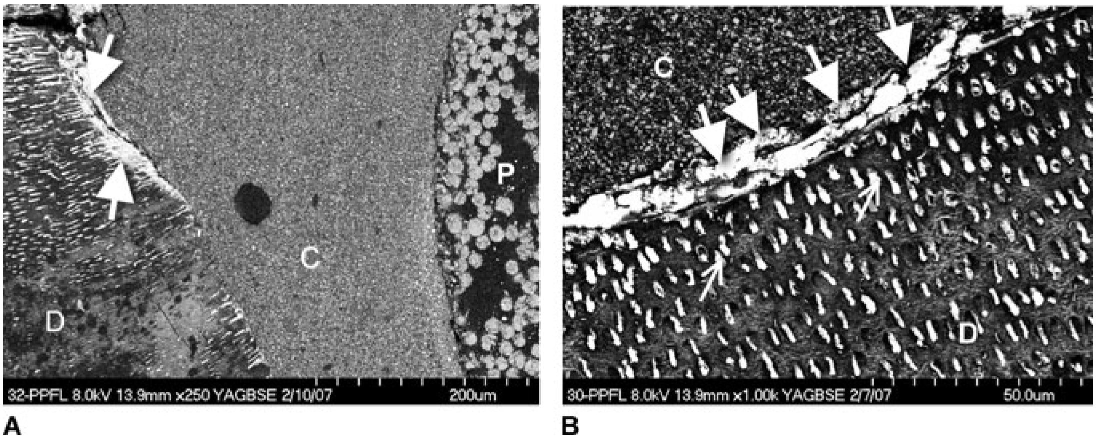

Figure 3 FESEM analyses of PP system: (A) dowel-resin cement and resin cement-dentin interfaces. Note the presence of silver infiltration at the cement-dentin interface (arrows) (backscattered FESEM image, slice 1); (B) silver infiltration into the dentinal tubules (narrow arrows) (backscattered FESEM image, slice 1). P = Dowel; C = Cement; D = Dentin; G = Residual gutta-percha. The μm units shown in the micrographs correspond to the entire scale of 10 divisions.

not associated with infiltration. The auto-mixing mechanism of RelyX Unicem cement used in group RX, and its placement in the root canal with an elongation canule, might explain the scarcity of voids at the RelyX Unicem-dentin interface. It has been demonstrated that when RelyX Unicem is applied under pressure, the number of porosities at the interface decreases.[35]

RelyX Unicem is a dual-cured self-adhesive resin cement that does not require any dentin pretreatment or a separate bonding agent,[35,36] making the technique relatively simple when compared with conventional resin cements. Some areas of debonding were observed at the resin cement-dentin interface for this cement. The debonding may be attributed to the lack of an effective smear layer penetration and/or dentin hybridization.[35,37] The specimen preparation for electron microscopy might also have played a role. Epoxy replicas are sometimes used to differentiate between real and artifactual gaps; however, taking into consideration that the SEM specimen processing was only performed after the ammoniacal silver nitrate challenge, and that the separation gaps were consistently associated with areas of silver infiltration, it was concluded that the silver ions were deposited before the SEM processing steps. Gaps were not artifactual, but possibly a result of the polymerization stress being higher than the bonding strength of the cement to root dentin.

RelyX Unicem has resulted in contradictory dentin bond strengths when used to lute fiber dowels upon light-curing.[36,38] While in one study[38] several dowels (everStick-Post, DT Light-Post, and FRC Fiber Post) luted with Variolink II resulted in higher push-out bond strengths than the same dowels luted with RelyX Unicem, another study[36] reported that RelyX Unicem resulted in the highest bond strengths, with or without thermocycling, when compared to Panavia F, Multilink, Variolink II, and PermaFlo DC. The latter study attributed the increased bond strengths to RelyX Unicem's moisture tolerance, as this self-adhesive cement forms water during the curing neutralization reaction.[36] The higher degree of conversion of RelyX Unicem compared to traditional resin cements[39] may also explain the lower degree of infiltration obtained in our study. When RelyX Unicem was used without light curing,[40] as in the present study, no statistical differences were found between the push-out bond strengths of dowels cemented with RelyX Unicem and those cemented with Excite DSC/Variolink II, an etch and rinse system.

In vivo studies suggest that the extension of structural flaws within the dentin/restoration interface increases gradually with time as a result of the loss of resin material at the interface as well as the degradation of collagen fibers in the hybrid layer.[41,42] This hydrolytic activity may result from the penetration of fluids[43] or from the water sorption along the interface.[44] In the present study, all dowel systems were used with self-etch adhesive materials. Theoretically, silver infiltration should not occur with self-etch adhesives, which may demineralize and infiltrate dentin simultaneously.[45] Our study is in agreement with another study that observed incomplete resin infiltration in superficial dentin collagen with self-etch adhesives[46] and with RelyX Unicem[35] at high magnification under TEM. The incomplete infiltration of self-etch adhesive materials may be caused by the reduced etching potential of the acidic monomers, or the presence of acidic hydrolytic adhesive components, creating potential sites for the degradation of the bonds.[47] Accordingly, the discrepancy between the depth of demineralized dentin and the depth of adhesive infiltration may be a consequence of residual water in the substrate or in the adhesive layer, leading to incomplete polymerization and increased permeability.[15,18,44]

The areas around residual gutta-percha showed silver infiltration. The unpredictable variation in root canal morphological features[48] may be responsible for the incomplete gutta-percha removal. Adhesion to root dentin requires a surface free of debris and pulpar remnants.[49] Studies have shown that not all walls of the root canal are contacted by instruments.[50] Additionally, the presence of residual gutta-percha in the prepared canals does not allow for adhesion between cement and dentin, leading to debonding at the adhesive interface, which prevents

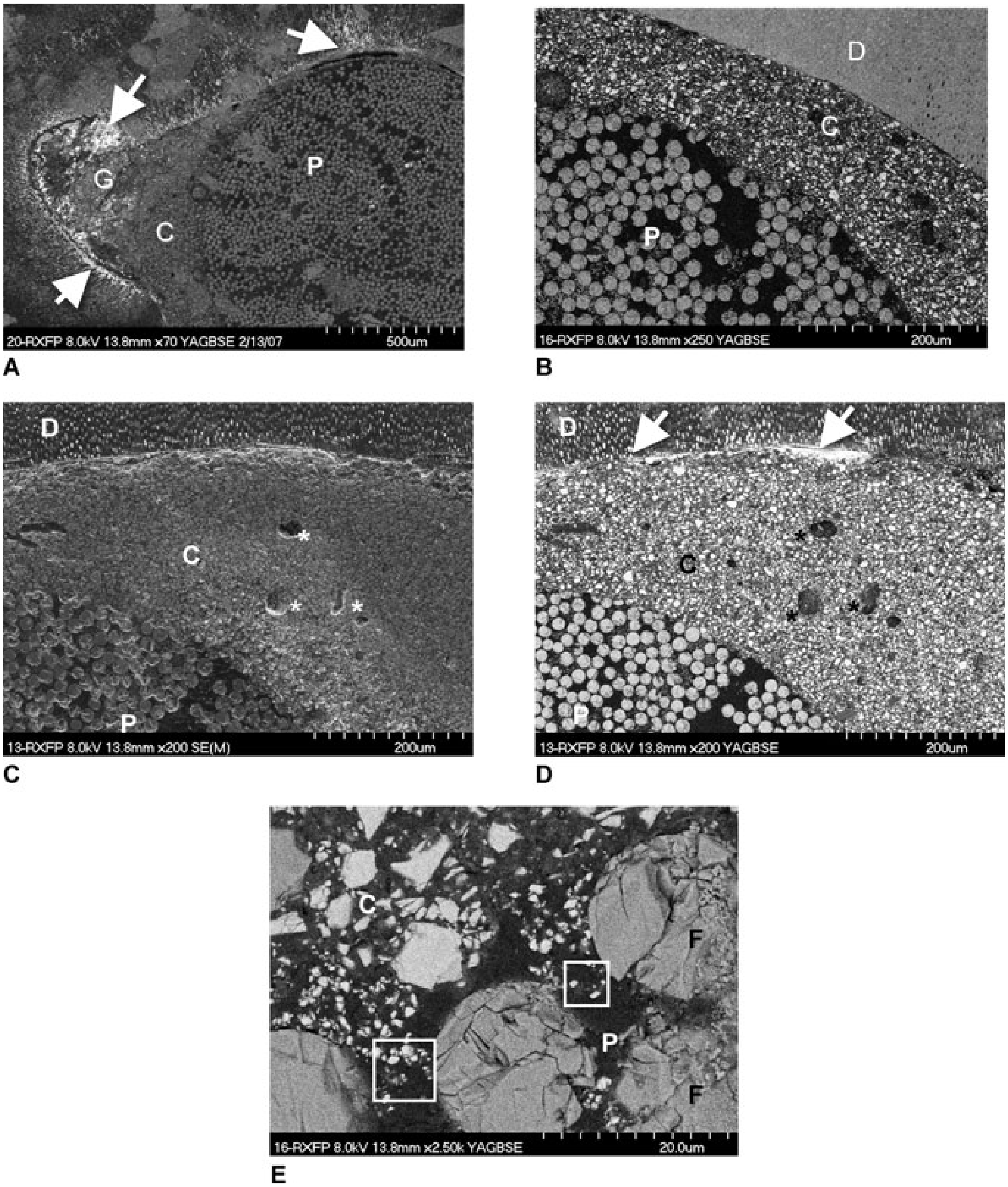

Figure 4 FESEM analyses of RX system: (A) residual gutta-percha with silver infiltration (arrows) (backscattered FESEM image, slice 2); (B) dowel-resin cement and resin cement-dentin interfaces, without silver infiltration (backscattered FESEM image, slice 2); (C) porosities (asterisks) within the cement layer (secondary FESEM image, slice 1); (D) secondary image shown in Fig 4C confirming the presence of porosities (asterisks); (E) high magnification (2500×) of the dowel-cement interface in group RX. The acidic characteristics of the mixed cement may have allowed its small particles to infiltrate the surface of the dowel (square). F = individual fibers (backscattered FESEM image, slice 2); P = Dowel; C = Cement; D = Dentin; G = Residual gutta-percha. The μm units shown in the micrographs correspond to the entire scale of 10 divisions.

a tight seal. Despite the careful preparation of the canal spaces, some canals had an elliptical shape in cross-section, which resulted in residual gutta-percha in areas that the preparation drill would not reach.

According to the manufacturer, everStick dowels are adjustable to fit the shape of the dowel space. Gates-Glidden drills are recommended to remove the gutta-percha, but no other calibrating drill is provided or recommended. One of the most difficult clinical features of the everStick dowels is their flexibility. The lack of rigidity of these dowels prior to their polymerization within the root canal makes it difficult for the dowel to reach the entire posthole depth and adapt to areas of the root canal in the middle and apical thirds. This, along with the thick unfilled adhesive layer applied on the EV dowels, which may undergo high shrinkage stresses, would explain why the EV group resulted in a greater number of infiltrated disks in the apical region. One of the specimens was infiltrated down to disk #6 (Table 4).

The ParaPost Fiber Lux is a recent addition from the respective manufacturer. Its predecessor, ParaPost FiberWhite, has resulted in acceptable push-out bond strengths to root canal dentin;[51] however, previous studies used a different version of the ParaBond self-etch adhesive used in the present study, known as ParaPost Cement Conditioner (Coltène/Whaledent). While the adhesive component is chemically similar, the use of a new nonrinse conditioner in ParaBond may preclude an effective bonding to root canal dentin.

This study analyzed the dowel systems as a whole. The manufacturer of everStick does not recommend a specific cement for use with its dowel material. The manufacturer also claims that there is interdigitation of the cement in the structure of the everStick dowel. Interdigitation of unfilled resin into the space between fibers was observed only when accessory dowels were added to the main dowel. Although the direct-technique concept behind the everStick dowel is promising in the rehabilitation of RCT teeth, more studies are needed to evaluate if these dowels allow interpenetration of the cement on their surface.

Silver infiltration was measured in polished specimens; however, there is some controversy with this method, since it is possible that sectioning and polishing of the specimens may cause smearing of silver across the specimen surface, giving an artificial reading of the silver deposition.[18] For that reason, when questions arose about the existence of silver smearing, a combination of backscattered with secondary modes at magnifications greater than 10,000× were used to confirm the presence of silver in the substrate or within the interface.

The specimens in the present study were not subjected to thermal or mechanical fatigue. ParaPost FiberWhite, the predecessor of ParaPost Fiber Lux, has a low mechanical fatigue resistance when compared to two other fiber dowels[10] and metal dowels.[52] Although a recent study found no statistical differences in root canal dentin bond strengths for fiber dowels subjected to mechanical fatigue,[53] the lack of thermal cycling may limit the extrapolation to clinical significance.[54]

The majority of the adhesive systems are tested in the laboratory 24 hours after the preparation of the specimens. This short interval fails to provide information about the long-term performance of the materials. Further studies are necessary to evaluate the behavior of glass-fiber dowel systems in terms of long-term sealing potential. Within the limitations of this study, the data supported the first null hypothesis that the sealing ability of everStick, the new IPN-based dowel, is not improved compared to the glass-fiber dowel system used as control, which was cemented with the same cement used with the everStick dowel. Regarding the second null hypothesis, the results warrant the acceptance of the alternative hypothesis, as the RX system (a glass-fiber dowel combined with a self-adhesive cement) resulted in better sealing ability into the root canal than the PP system, a glass-fiber dowel combined with the dual-cured resin cement.

Conclusion

The use of the IPN technology in EV did not improve the root-wall sealing ability compared with the control group PP. The self-adhesive cement used in the present study showed potential to be used as a fiber dowel-luting agent.

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References

1. Reid L, Kazemi R, Meiers J: Effect of fatigue testing on core integrity and post microleakage of teeth restored with different post systems. J Endod 2003;29:125-131.
2. Malferrari S, Monaco C, Scotti R: Clinical evaluation of teeth restored with quartz fiber-reinforced epoxy resin posts. Int J Prosthodont 2003;16:39-44.
3. Vichi A, Grandini S, Davidson C, et al: An SEM evaluation of several adhesive systems used for bonding fiber posts under clinical conditions. Dent Mater 2002;18:495-502.
4. Torbjörner A, Karlsson S, Odman P: Survival rate and failure characteristics for two post designs. J Prosthet Dent 1995;73:439-444.
5. Sirimai S, Riis DN, Morgano SM: An in vitro study of the fracture resistance and the incidence of vertical root fracture of pulpless teeth restored with six post-and-core systems. J Prosthet Dent 1999;81:262-269.
6. Asmussen E, Peutzfeldt A, Heitmann T: Stiffness, elastic limit, and strength of newer types of endodontic posts. J Dent 1999;27:275-278.
7. Pegoretti A, Fambri L, Zappini G, et al: Finite element analysis of a glass fibre reinforced composite endodontic post. Biomaterials 2002;23:2667-2682.
8. Bitter K, Priehn K, Martus P, et al: In vitro evaluation of push-out bond strengths of various luting agents to tooth-colored posts. J Prosthet Dent 2006;95:302-310.
9. Schwartz RS, Robbins JW: Post placement and restoration of endodontically treated teeth: a literature review. J Endod 2004;30:289-301.
10. Grandini S, Goracci C, Monticelli F, et al: Fatigue resistance and structural characteristics of fiber posts: three-point bending test and SEM evaluation. Dent Mater 2005;21:75-82.
11. Bell A, Lassila L, Kangasniemi I, et al: Bonding of fibre-reinforced composite post to root canal dentin. J Dent 2005;33:533-539.
12. Mannocci F, Sherriff M, Watson T, et al: Penetration of bonding resins into fibre-reinforced composite posts: a confocal microscopic study. Int Endod J 2005;38:46-51.
13. Wu M, Wesselink P: Endodontic leakage studies reconsidered: Part I. Methodology, application and relevance. Int Endod J 1993;26:37-43.
14. Sano H, Shono T, Takatsu T, et al: Microporous dentin zone beneath resin-impregnated layer. Oper Dent 1994;19:59-64.
15. Sano H, Takatsu T, Ciucchi B, et al: Nanoleakage: leakage within the hybrid layer. Oper Dent 1995;20:18-25.
16. Sano H: Microtensile testing, nanoleakage, and biodegradation of resin-dentin bonds. J Dent Res 2006;85:11-14.
17. Okuda M, Pereira P, Nakajima M, et al: Long-term durability of resin dentin interface: nanoleakage vs. microtensile bond strength. Oper Dent 2002;27:289-296.

18. Li H, Burrow M, Tyas M: Nanoleakage patterns of four dentin bonding systems. Dent Mater 2000;16:48-56.
19. Pioch T, Staehle H, Schneider H, et al: Effect of intrapulpal pressure simulation in vitro on shear bond strengths and hybrid layer formation. Am J Dent 2001;14:319-323.
20. Torabinejad M, Ung B, Kettering J: In vitro bacterial penetration of coronally unsealed endodontically treated teeth. J Endod 1990;16:566-569.
21. Bouillaguet S, Troesch S, Wataha J, et al: Microtensile bond strength between adhesive cements and root canal dentin. Dent Mater 2003;19:199-205.
22. Wiegand A, Buchalla W, Attin T: Review on fluoride-releasing restorative materials—fluoride release and uptake characteristics, antibacterial activity and influence on caries formation. Dent Mater 2007;23:343-362.
23. Tay F, Pashley D, Yoshiyama M: Two modes of nanoleakage expression in single-step adhesives. J Dent Res 2002;81: 472-476.
24. Sano H, Yoshiyama M, Ebisu S, et al: Comparative SEM and TEM observations of nanoleakage within the hybrid layer. Oper Dent 1995;20:160-167.
25. Ferrari M, Mannocci F, Vichi A, et al: Effect of two etching times on the sealing ability of Clearfil Liner Bond 2 in Class V restorations. Am J Dent 1997;10:66-70.
26. Spencer P, Swafford J: Unprotected protein at the dentin-adhesive interface. Quintessence Int 1999;30:501-507.
27. Van Meerbeek B, Yoshida Y, Lambrechts P, et al: A TEM study of two water-based adhesive systems bonded to dry and wet dentin. J Dent Res 1998;77:50-59.
28. Feilzer A, de Gee A, Davidson C: Setting stress in composite resin in relation to configuration of the restoration. J Dent Res 1987;66:1636-1639.
29. Tay F, Loushine R, Lambrechts P, et al: Geometric factors affecting dentin bonding in root canals: a theoretical modeling approach. J Endod 2005;31:584-589.
30. Davidson C, de Gee A: Relaxation of polymerization contraction stresses by flow in dental composites. J Dent Res 1984;63:146-148.
31. Perdigão J, Gomes G, Augusto V: The effect of dowel space on the bond strengths of fiber posts. J Prosthodont 2007;16:154-164.
32. Ferrari M, Vichi A, Grandini S, et al: Efficacy of a self-curing adhesive-resin cement system on luting glass-fiber posts into root canals: an SEM investigation. Int J Prosthodont 2001;14:543-549.
33. Alster D, Feilzer A, de Gee A, et al: The dependence of shrinkage stress reduction on porosity concentration in thin resin layers. J Dent Res 1992;71:1619-1622.
34. Feilzer AJ, De Gee AJ, Davidson CL: Setting stresses in composites for two different curing modes. Dent Mater 1993;9:2-5.
35. De Munck J, Vargas M, Van Landuyt K, et al: Bonding of an auto-adhesive luting material to enamel and dentin. Dent Mater 2004;20:963-971.
36. Bitter K, Meyer-Lueckel H, Priehn K, et al: Effects of luting agent and thermocycling on bond strengths to root canal dentine. Int Endod J 2006;39:809-818.
37. Goracci C, Sadek F, Fabianelli A, et al: Evaluation of the adhesion of fiber posts to intraradicular dentin. Oper Dent 2005;30:627-635.
38. Goracci C, Tavares AU, Fabianelli A, et al: The adhesion between fiber posts and root canal walls: comparison between microtensile and push-out bond strength measurements. Eur J Oral Sci 2004;112:353-361.
39. Gertha HUV, Dammaschke T, Züchner H, et al: Chemical analysis and bonding reaction of RelyX Unicem and Bifix composites—a comparative study. Dent Mater 2006;22:934-941.
40. Kececi AD, Ureyen Kaya B, Adanir N: Micro push-out bond strengths of four fiber-reinforced composite post systems and 2 luting materials. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2008;105:121-128.
41. Hashimoto M, Ohno H, Kaga M, et al: In vivo degradation of resin-dentin bonds in humans over 1 to 3 years. J Dent Res 2000;79:1385-1391.
42. Sano H, Yoshikawa T, Pereira P, et al: Long-term durability of dentin bonds made with a self-etching primer, in vivo. J Dent Res 1999;78:906-911.
43. Okuda M, Pereira P, Nakajima M, et al: Relationship between nanoleakage and long-term durability of dentin bonds. Oper Dent 2001;26:482-490.
44. Tay F, Hashimoto M, Pashley D, et al: Aging affects two modes of nanoleakage expression in bonded dentin. J Dent Res 2003;82:537-541.
45. Suppa P, Breschi L, Ruggeri A, et al: Nanoleakage within the hybrid layer: a correlative FEISEM/TEM investigation. J Biomed Mater Res 2005;73:7-14.
46. Perdigão J, Lopes M, Gomes G: Interfacial adaptation of adhesive materials to root canal dentin. J Endod 2007;33:259-263.
47. Carvalho R, Chersoni S, Frankenberger R, et al: A challenge to the conventional wisdom that simultaneous etching and resin infiltration always occurs in self-etch adhesives. Biomaterials 2005;26:1035-1042.
48. Mjör IA, Smith MR, Ferrari M, et al: The structure of dentine in the apical region of human teeth. Int Endod J 2001;34: 346-353.
49. Schwartz R: Adhesive dentistry and endodontics: Part 2. Bonding in the root canal system-the promise and the problems: a review. J Endod 2006;32:1125-1134.
50. Peters O: Current challenges and concepts in the preparation of root canal systems: a review. J Endod 2004;30:559-567.
51. Kurtz JS, Perdigão J, Geraldeli S, et al: Bond strengths of tooth-colored posts—effect of sealer, dentin adhesive, and root region. Am J Dent 2003;16:31A-36A.
52. Goto Y, Nicholls JI, Phillips KM, et al: Fatigue resistance of endodontically treated teeth restored with three dowel-and-core systems. J Prosthet Dent 2005;93:45-50.
53. Bottino MA, Baldissara P, Valandro LF, et al: Effects of mechanical cycling on the bonding of zirconia and fiber posts to human root dentin. J Adhes Dent 2007;9:327-331.
54. Kalkan M, Usumez A, Ozturk A, et al: Bond strength between root dentin and three glass-fiber post systems. J Prosthet Dent 2006;96:41-46.

